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Investigation of the Relationship between Schimazek's F-Abrasiveness Factor and Current Consumption in Rock Cutting Process

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ABSTRACT

Predicting the current consumption of cutting machines in cutting building stones can be one of the most fundamental steps to achieve optimal conditions from energy consumption in the building stone cutting industry. Therefore, it is necessary to study the relationship between the operational characteristics of the machine and the work piece with the amount of consumed energy by the machine. In this paper, an attempt has been made to provide a precise model for predicting the current consumption of cutting machines using statistical studies. For this purpose, laboratory studies were performed under different operational conditions such as different depths of cut (15, 22, 30, and 35 mm) and different feed rates (100, 200, 300, and 400 cm/min). During the sawing process, 12 samples of soft and hard rock were studied by using a cutting machine on a laboratory scale (with the ability to change machining parameters and equipped with measuring current consumption). Following laboratory studies, rock samples were transferred to the rock mechanics laboratory to determine Schimazek's F-abrasiveness factor. After determining the abrasion of the samples, statistical studies were performed by using the SPSS software. Thus, the new statistical models were presented to predict the current consumption of the cutting machine based on the abrasion of the building stone sample, cutting depth, and the progress rate of the workpiece as an independent variable. The proposed statistical models can be used with high reliability to estimate the current consumption in the cutting process.

Keywords: **Current consumption, Machine parameters, Schimazek's F-abrasiveness factor, Statistical models**

1. INTRODUCTION

Observing the inefficiency and failure of technical management of energy consumption in some industrial processes and the resulting adverse environmental impacts reveal that optimization of energy consumption in industries and to carry out many projects in this connection are needed. Achieving this goal requires an accurate study of industries to reduce production costs while finding solutions to optimize energy consumption. Complete knowledge of building stones and evaluation of the performance capability of cutting machines in processing factories will lead to improve processing speed and increase production by designers and production planners. Proper application of these tools on the one hand and knowing and carefully investigating their performance, on the other hand, can significantly contribute to increased efficiency and quality of processed building stones. Relatively good studies have been conducted at various industrial and laboratory scales in the field of building stone cutting capabilities. Tutmez et al. developed a multifactorial fuzzy classification to evaluate the salability of building stones [1]. Mikaeil et al. developed the statistical models to predict the production rate of diamond wire saws in carbonate rock cutting [2]. Mikaeil et al. evaluated the saw ability ranking of

carbonate rock using fuzzy analytical hierarchy process and TOPSIS approaches [3]. Ghaysari et al. predicted the performance of diamond wire saw concerning texture characteristics of rock [4]. Ataei et al. predicted the production rate of diamond wire saw using statistical analysis according to some important properties of building stone [5]. Ataei et al. used a fuzzy analytical hierarchy process approach (FAHP) to rank the saw ability of carbonate rock [6]. Mikaeil et al. ranked the saw ability to build stone using Fuzzy Delphi and multi-criteria decision-making techniques [7]. Sadegheslam et al. predicted the production rate of diamond wire saws using multiple nonlinear regression analyses in carbonate rock cutting [8]. Mikaeil et al. studied the Sawability of building stone by using PROMETHEE [9]. Tumac investigated the performance of large diameter circular saws based on Schmidt hammer and other properties for some Turkish carbonate rocks [10]. Aryafar and Mikaeil. estimated the ampere consumption of building stone sawing machines using artificial neural networks [11]. Tumac used the artificial neural network to predict the saw ability performance of large diameter circular saws [12]. Almasi et al. predicted the building stone cutting rate based on rock properties and device pullback amperage (PA) in quarries using the M5P model tree [13]. Almasi et al. analyzed the bead wear in diamond wire sawing by considering the rock properties and production rate [14]. Almasi et al. developed a new rock classification based on the abrasiveness, hardness, and toughness of rocks and PA for predicting the hard building stone saw ability in quarrying [15]. Akhyani et al. evaluated the cutting performance of the diamond saw machine using an artificial bee colony (ABC) algorithm [16]. Kamran et al. ranked the saw ability to build stones using different MCDM methods [17]. Mikaeil et al. applied multivariate regression to predict the performance of diamond wire saw [18]. Aryafar et al. used metaheuristic algorithms to achieve the optimal clustering of sawing machine vibration [19]. Aryafar et al. studied the application of soft computing to evaluate the performance of stone sawing machines [20]. Akhyani et al. investigated the effect of toughness and brittleness indexes on ampere consumption and the wear rate of a circular diamond saw [21]. Mikaeil et al. predicted the performance of circular saw machines using the imperialist competitive algorithm and fuzzy clustering technique [22]. Mikaeil et al. estimated the wear rate of diamond wire saw using an adaptive neuro-fuzzy inference system and group method of data handling-type neural network [23]. Tumac and Shaterpour-Mamaghani estimated the saw ability of large diameter circular saws based on the classification of natural stone types according to the geological origin [24]. Akhyani et al. used the combining the fuzzy RES with GA to predict the wear performance of circular diamond saw in the hard rock cutting process [25]. Dormishi et al. evaluated the performance of gang saw using hybrid ANFIS-DE and hybrid ANFIS-PSO algorithms [26]. Dormishi et al. evaluated the gang saws' performance in the carbonate rock cutting process using the feasibility of intelligent approaches [27]. Haghshenas et al. developed a new conventional criterion for the performance evaluation of gang saw machines [28]. Hosseini et al. investigated the effect of coolant and lubricant fluids on the performance of cutting disks [29]. Mikaeil et al. used the harmony search algorithm to evaluate the performance of diamond wire saw [30]. Mohammadi et al. evaluated the performance of chain saw machines in building stone cutting by using neural network models [31]. Hosseini et al. investigated experimentally the effect of coolant and lubricant fluids in the maximum electrical current based on rock physical and mechanical properties [32]. Hosseini et al. studied the effect of the cooling and lubricant fluid on the cutting performance of building stone using the artificial intelligence models [33].

2. MATERIALS AND METHODS

In this paper, the attempt was made to investigate the relationship between rock abrasion and the operating characteristics of the cutting machine with the current consumption of the cutting machine using statistical studies. For this purpose, firstly, the mechanism of stone cutting and the effective parameters in stone cutting capability were investigated, and later laboratory studies were carried out on 12 samples of building stone. Then, statistical models were provided to predict the current consumption. Finally, the results of this study were analyzed using statistical tests (t and F tests).

2.1. STONE CUTTING PROCESS

In general, 31 boreholes along Tabriz Metro Line 1 were collected to evaluate the liquefaction potential and estimate the probable settlement in soil layers in the study area. Approximately the length of Tabriz Metro Line 1 is equal to 17.2 Km. As shown in Figure 1, a part of this path is located underground

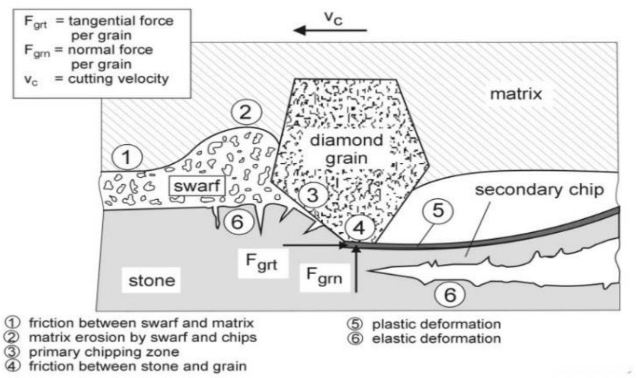

Figure 1. Interaction of existing forces between diamond grain and stone scratched surface [34].

Generally, the effective parameters in the building stone cutting process can be divided into three main parts, including a) workpiece characteristics (building stone), b) cutting specifications, including operational parameters and cutting plan properties, and c) managerial characteristics such as operator skills and working environmental conditions analyzed. From among these parameters, operational parameters and cutting design properties are viewed as controllable parameters or dependent parameters, and parameters related to building stone characteristics are considered as uncontrollable parameters or independent parameters in the building stone cutting process. Each of these parameters influences the efficiency and production capacity of the cutting process. In this regard, assuming things constant (devise conditions and cutting equipment as well as operator skills), building stone properties will be of significance with regards to cutting performance. Building stone profile is one of the effective parameters in the cutting process, especially in the chip formation process. Building stone, as the host of cutting operations, plays a vital role in the cutting and production process. Building stone properties determine the conditions, quality, and quantity of the interaction between the building stone and the machine, hence, the mechanism of chip formation and tool advance are highly affected. Because of the wide range of geo-mechanical building stone characteristics to facilitate the analysis and study of these parameters, they can be divided into three groups of physical, mechanical, and structural characteristics. Figure 2 shows the effective parameters in the building stone cutting process.

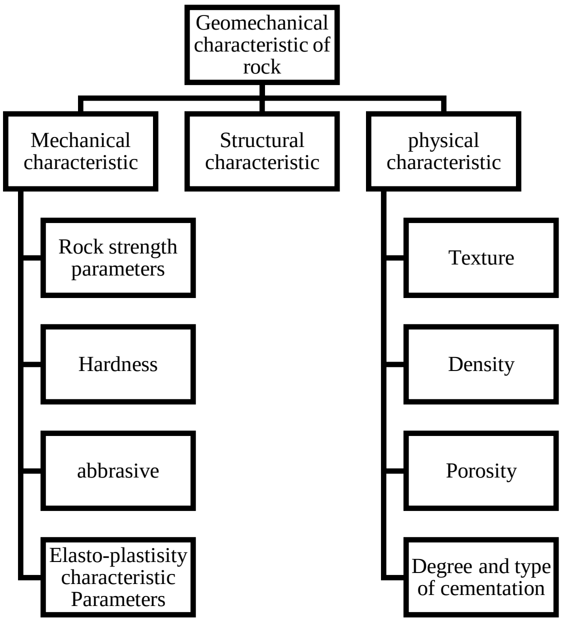

Figure 2. Effective parameters on stone cutting process.

2.2. SCHIMAZEK'S F-ABRASIVENESS FACTOR

Abrasiveness is referred to some property of building stone that can destroy steel-made bits, tungsten, or diamond carbs. Abrasion depends on the hardness of the minerals, but the shape of the granules and the cleavage also affect the quality of this property. For this reason, not long years ago, when only steel drills were being used, the life of these drills in quartz-containing stones such as sandstone was a few centimeters. Although quartz is thought to be harder than steel, the form of the particles has not been ineffective in reducing drill life. This problem was removed by replacing steel drills of tungsten carbide instead of steel drills. Sharp, angular particles compared to round particles create deep scratches on the drill and prevent the energy from transferred to the drilling surface cause a cutting on the building stone. On the other hand, small and round particles cause polishing of the head and slow cutting. Abrasion in stones generally depends on three factors: quartz content, granule size, and building stone cutting strength [35]. In this connection, the amount of silica or quartz, in general, has been highly emphasized. It is possible to determine the abrasiveness of stones based on the existence of silica. Stones that have less silica, such as dolomite or lime, have less abrasiveness, and conversely, stones containing more SiO2, such as silica sandstone, have more abrasiveness. Thus, various qualitative and quantitative indicators have been provided to evaluate the stone abrasiveness, among which Schimazek's F-abrasiveness factor was selected as the most widely used method for determining the abrasiveness of the building stones studied in this research. This index was presented in 1970 by Schimazek and Natz. The general relationship of this index is as follows.

$$F = \frac{EqQtz \times \varphi \times BTS}{100} \tag{1}$$

where EqQtz represents the percentage of quartz degree containing the stone equivalent, granule size in millimeters, with BTS indicating indirect tensile strength (Brazilian test). The granule size is determined using thin sections and weight averaging pf granule size and the amount of indirect tensile strength by way of the experiment. Among the above parameters, the quartz percentage contains one of the most sensitive and widely used parameters related to stone abrasiveness. This index is based on the fact that to what extent ach mineral creates a percentage of abrasiveness from a quart by the Mohs scale hardness. The general relation for determining EqQtz is as follows:

$$EqQtz = \sum_{i=1}^{n} A_i . R_i \tag{2}$$

Where

A_i: Index of minerals content.

R_i: Rosiwal abrasion (Rosiwal abrasion of the rock can be calculated using the mouse stiffness according to the equation shown in Figure 3.

n: Minerals number

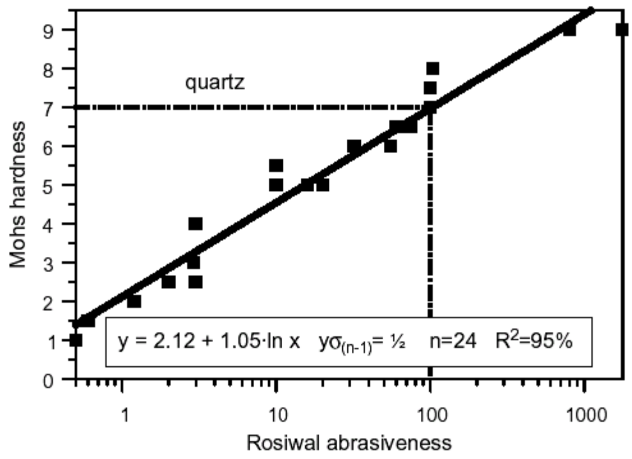

Figure 3. Relationship between rock resilience and mohs hardness [36].

If it follows from this figure, the amount of EqQtz for the quartz mineral is 100%. By decreasing the amount of quartz or other hardness of the minerals, the amount of rock abrasion decreases logarithmically.

2.3. FIELD AND LABORATORY STUDIES

For designing and presenting a statistical model to predict the current consumption of the cutting machine, various tests were performed on 12 building stone samples in different operational conditions. Statistical data were collected in two parts: laboratory and field data collection based on the ISRM standards (ISRM 1981). In order to study the behavior of building stone samples under different operating conditions (machine work), a cutting machine was developed on a lab scale. The specifications of the cutting machine, along with the specifications of the workpiece and cutting tools, are given below.

2.4. CUTTING MACHINE CHARACTERISTICS

The cutting machine has been designed so that it is possible to change the working machining parameters such as cutting depth and propulsion rate, with minor changes made to the machine. The different components of this machine include the machine bed (consisting of two guide rails for the moving machine table), the upper part of the chassis (the place at which the main axis of the machine is laid), and the lower part of the chassis (to collect mire and mud, water and cutting chips) (Figure 4). The moving table of the machine has a flat surface on which the building stone pieces are fixed for cutting operations. The machine table gets moving on the machine rails by a wheel and chain mechanism attached to a hydraulic motor. Using a hydraulic system allows for the control and tuning of the table speed, which is the same propulsion speed. The transmission of force to the main axis is done by a pulley and a rubber strap. The cutting disc is laid and fastened between the two cast iron washers by a bolt mechanism. The whole spindle is fixed on a steel bed fixed by the main bearing bed. The spindle bed bearing is in such a way that it allows a very limited rotational motion of approximately 8. The main spindle motor with a 7.5 kW power is fixed above the bed. Vertical propulsion is performed by a combined mechanism with a hydraulic motor. This

mechanism, which is based on bolts and nuts, can be tuned with a cutting depth of an accuracy of 0.01 mm. A hydraulic unit is used to run the moving motors of the table (horizontal propulsion) and the throat bed (vertical propulsion). This system allows for the control of the propulsion speeds. The electrical circuit of the device makes it possible to control the machine propulsion movements in three manuals, semi-automatic and fully automatic modes. Propulsion speed is measured by an electronic counter. During the experiment, the current consumption of the machine was recorded and measured by an accurate ammeter under different machining conditions in different rates of propulsion (100, 200, 300, and 400 cm/min) and different cutting depths (15, 22, 30 and 35 mm). In all experiments, the cutting action was in a positive position (to move the workpiece in the same direction as the rotation of the disc) and water was used as the cooling fluid.

Figure 4. Schema of cutting machine.

2.5. BUILDING STONE CHARACTERISTICS

To investigate the relationship between building stone sample hardness, cutting depth, and propulsion rate with energy consumption, the second part of laboratory studies was performed on the studied building stone samples. For this purpose, 12 building stone samples, including 5 samples of hard building stone and 7 samples of soft building stone, were sampled. The amount of energy consumption under different operating circumstances was measured and recorded in the laboratory. To determine the abrasiveness properties of the samples, a thin section of each sample was first prepared from the specific part of the studied building stones, and later the amount of quartz and granule size along with tensile strength were studied to determine the Schimazek's F-abrasiveness factor. A thin section sample provided for the study is shown in Figure 5. Using this section, the quartz values of the building stone sample along with the granule size for the studied building stone samples were calculated to determine the abrasiveness factor. The laboratory studies are given in Table 1.

Figure 5. Thin section digital format of Chayan granite sample.

Table 1. Laboratory studies of the studied rocks

Mine name	Stone type	EqQtz (%)	BTS (MPa)	GS (mm)	SF-a (N/mm)
Ghaleh Khargushi	Granite	65.5	8.52	2.9	**14.24**
Chayan	Granite	60.06	15	0.87	**7.6**
Nehbandan	Granite	64.3	9.2	4.1	**24.25**
Khoshtinat	Granite	32.2	8.3	3.9	**10.42**
Khatam Granite	Granite	30.3	7.4	3.8	**8.5**
Zolfaghar Ali	Marble	3.6	6.8	0.55	**0.135**
Gol Sang	Marble	3.4	7.1	0.45	**0.109**
Azar Shahr	Travertine	2.8	4.3	1.01	**0.122**
Haji Abad	Travertine	2.6	5.6	0.85	**0.124**
Darreh Bokhari	Travertine	2.7	5.4	0.87	**0.127**
Salsali	Marble	3.2	6.3	0.52	**0.105**
Haftuman	**Marble**	**4**	**7.2**	**0.6**	**0.173**

EqQtz: Equal Quartz Content, **BTS**: Brazilian Tensile Strength, **GS**: Grain size, **SF-a**: Schimazek's F-abrasiveness.

2.6. CUTTING TOOL CHARACTERISTICS

In all experiments, the cut was in a positive position (moving the workpiece in the same direction to the rotation of the disc), and water was used as the cooling fluid. In cutting experiments, two hard and soft metal circular diamond saw with a diameter of 41 cm, and a thickness of 2.7 mm was used. Twenty-eight diamond segments with dimensions of 40 × 10 × 3 mm were soldered around the steel body. Synthetic diamond beads in the form of octagonal cube crystals with a 40.50 mesh for hard-cutting disc and a 30/40 mesh for soft-cutting disc and weight percentages of 25 to 30 and 30 to 40 for 2 soft and hard circular diamond saw, respectively, were distributed on a metal band. Specifications of circular diamond saw that are used in cutting tests are given in Table 2.

Table 2. Specifications of circular diamond saw used in cutting experiments.

Disc type	Diamond used in bands (%)	Diamond crystal mesh size
Hard	3-40	**40/50**
Soft	**25-30**	**30/40**

Thus, having conducted laboratory studies, as many as 223 samples of cutting were carried out under different machining conditions on the building stones studied, of which 112 samples belong to soft building stones and 111 samples for hard building stone samples.

3. RESULTS AND DISCUSSION

In this part of the research, statistical studies on laboratory results were done to investigate the relationship between the current consumption of the cutting machine with the hardness of the building stone samples and operational parameters by using the SPSS software; later, the statistical relationships were statistically evaluated according to tests. The relationships obtained from statistical studies are provided as follows.

$$I_H = \frac{D_c^{0.681} \times F_r^{0.498} \times SF - a^{0.093}}{10^{1.162}} \quad \text{(Model 1)}$$

$$I_S = \frac{D_c^{0.539} \times F_r^{0.43} \times SF - a^{0.243}}{10^{0.525}} \quad \text{(Model 2)}$$

Where Is is current consumption for soft building stones, IH is current consumption for the hard building stone, Dc is the depth of cut, and Fr is feed rate. In all the above relationships, the current consumption of the device was considered as a dependent parameter, and the operational or machining specifications and abrasiveness of the building stone sample were viewed as independent parameters. Statistical tests were used to evaluate and control the obtained relationships. The F test was used to control for the relationship significance, and the t-test was used to control for the significance of each of the independent variables. The values of each of the above parameters were determined separately for each relationship using the SPSS statistical software. The results of statistical studies (correlation coefficient and F and t-tests) are given in Table 3.

Table 3. Results of statistical studies

Model	Parameters	coefficients	Standard Error	F	F Table	t	t Table	R
1	Constant	-1.162	0.118	129.2	5.21	-9.8	1.66	**0.9**
	D_c	0.681	0.055			12.3		
	F_r	0.498	0.022			16.9		
	SF-a	0.093	0.037			2.5		
2	Constant	-0.525	0.074	365.5	5.56	-7.02	1.76	**0.96**
	D_c	0.539	0.027			19.9		
	F_r	0.43	0.016			27.6		
	SF-a	**0.243**	**0.054**			**4.5**		

According to Table 3, the F value obtained from the distribution table with the confidence level of 99% is greater than the F value obtained from the relationship. Thus t the null hypothesis was rejected by stating that there is no linear relationship between the dependent variable and independent variables. It was concluded that at least one of the fitting coefficients is not zero. After controlling for the overall significance of the relationship with the F-test, the significance of each of the independent variables is controlled for by the t-test. Using this test, one can test the hypothesis that each of the coefficients of independent variables is zero. Since the t value obtained from the corresponding distribution table with a confidence level of 90% is greater than the t values obtained from the independent variables, thus, the hypothesis that the coefficients of the independent variables are zero can be rejected. One of the important points to be considered in statistical analysis, especially for providing statistical relationships is the existence of logical coefficients, or in other words, following the relationship of the inherent nature of the process. In the presented relationships in this research, the values of logical coefficients in the relations are consistent with the scientific logic of the subject, being acceptable from the view of logical coefficients. Another method for evaluating statistical relationships is the scatter of predicted and real points relative to the half-making line 1: 1. The predicted points scatter relative to the actual values of the current consumption of the cutting machine for the two categories of data (training and test data) are shown in Figures 6 and 7. The higher the density of these points compared to the half-making line, the more accurate the relationship. According to the explanations provided, it can be inferred that the presented relationships have good accuracy in estimating and predicting the amount of current consumption.

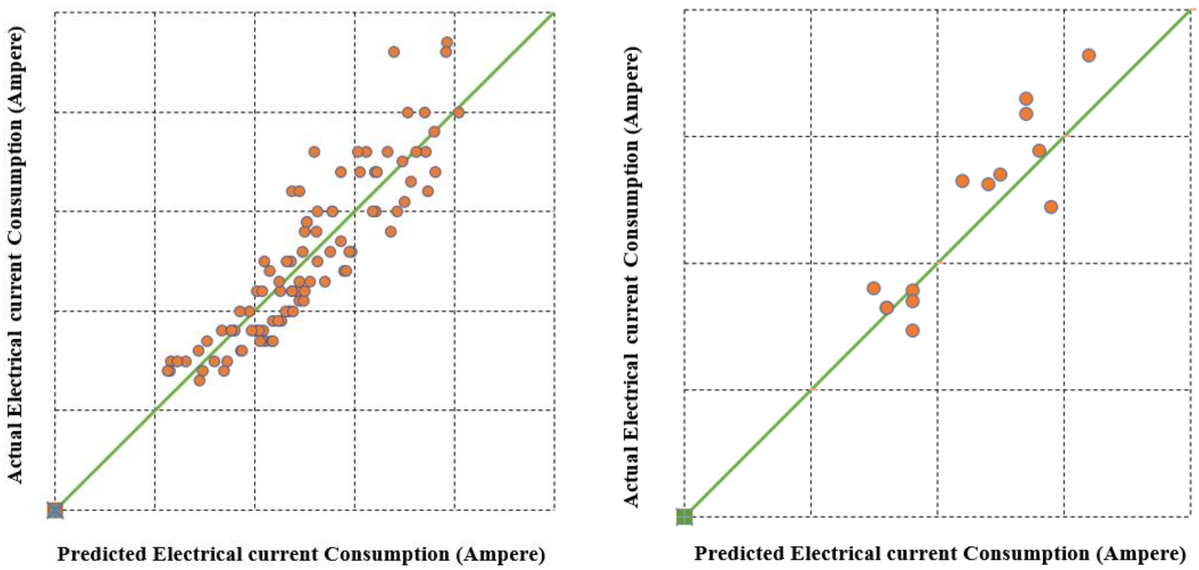

Figure 6. Scattering of predicted and actual points relative to the 1: 1 line (Hard rock).

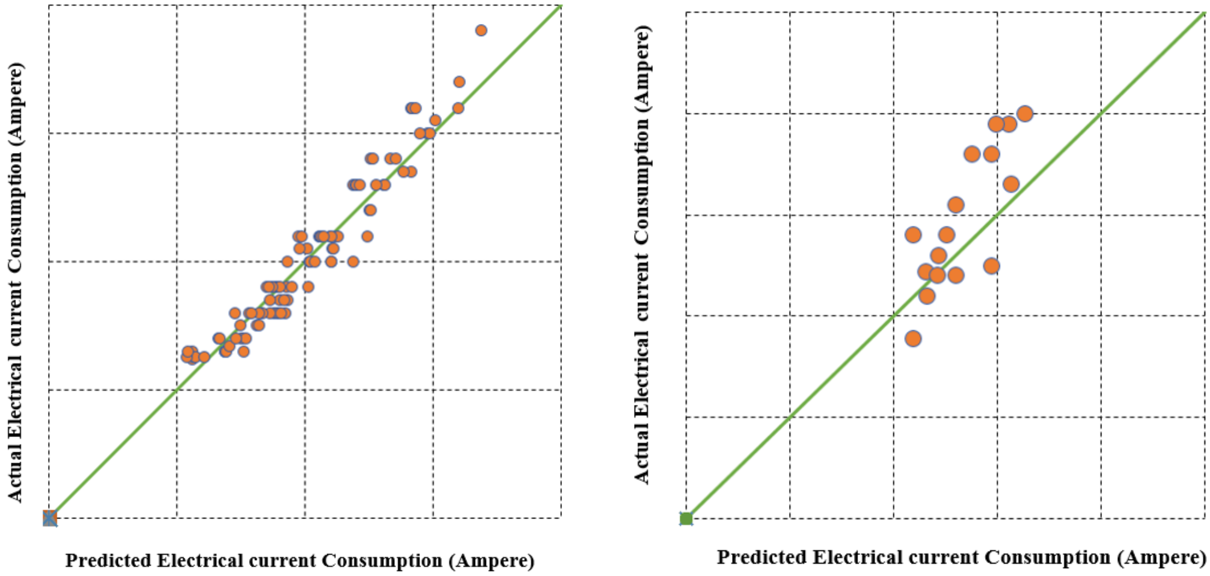

Figure 7. Scatter of predicted and actual points relative to the 1: 1 line (Soft rock).

4. CONCLUSION

In this research, the relationship between the current consumption of the cutting machine and the operational parameters was attempted to be investigated. One of the important mechanical properties of the building stone was also considered by conducting accurate experiments and statistical studies. To this end, 12 samples of building stones were selected from the family of hard and soft building stones. The amount of current consumption of the cutting machine under different machining conditions was recorded in the laboratory. The samples were then transferred to a building stone mechanics laboratory for testing, and the abrasiveness rate was determined using Schimazek's F-abrasiveness factor. After all these steps, statistical studies were performed on the statistical population. The results of multivariate fitting showed that in both groups of the studied building stones, the amount of current consumption of the device increases as the number of abrasiveness increases. In this study, the obtained relationships from statistical studies were examined using t and F tests to control for and to show the significance of the relationship and coefficients. The findings of these studies suggested that as the level of reliability and good correlation coefficient rises, the current consumption of cutting machines can be evaluated and predicted based on the machining characteristics and building stone sample abrasiveness.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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